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I /J BAND LOW-COST CROSSED-FIELD AMPLIFIER.(U)

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I/J BAND LOW-COST CROSSED-FIELD AMPLIFIER

Robert R. Moats
NORTHROP DEFENSE SYSTEMS DIVISION
Electron Tube Section
Des Plaines, IL 60018

NOVEMBER 1979

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3 kW peak pulse power and 1 kW average power output, 20 dB gain, 2-4 GHz; and for phased-array radar, 2 kW peak pulse power output at 10-15% duty, 25 dB gain, 3.0-3.6 GHz. Objective specifications for I/J-band devices are 1 kW peak pulse power and 200W average power output, 20 dB gain, 8.5-17 GHz.

A previously built E/F-band CFA with laser-cut substrate was tested to determine its performance with respect to the phased array requirements. It was concluded that additional circuit length is required for increased gain. In addition, it will be desirable to add attenuation in the small-signal part of the tube to improve stability in the electronic warfare mode.

A first round of I/J-band large-signal calculations was performed. It was concluded that a circuit pitch of 0.014" is desirable, and that cathode-to-ground voltage should be about 6500 V. An initial design for an I/J-band operating CFA has been completed, based on the results of these calculations.

Additional cold-test models have been designed. They will be actual size, including length, and will be designed to incorporate an input/output matching configuration similar to the operating CFA design. Attenuation is of particular concern.

The existing crossed-field beam tester is to be modified to test electron guns for the I/J-band CFA. Parts for the necessary changes are being designed.

A coaxial window designed for an X-band CFA has been tested for matching up to 18 GHz, and matching was good up to 14 GHz. This window is to be scaled to produce a good match up to 18 GHz.

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SECTION I

INTRODUCTION

The effort in this program is directed toward the development of a high-power broad-band low-cost I/J-band linear format crossed-field amplifier (CFA) for electronic warfare. A laser-cut shaped-substrate meander line circuit is used. In addition, E/F-band CFA's of similar construction are to be built which can be applied either to electronic warfare or phased-array radar.

The laser-cut shaped-substrate meander circuit, a concept originated by ERADCOM personnel, is potentially a major cost saving measure, replacing a set of 80 or more individual insulators with a single part. Furthermore, the individual insulators for I/J-band would be so small as to be impractical.

The objective specifications for the E/F-band operating model for electronic warfare are as follows:

Frequency	2-4 GHz
Peak Power Output	3 kW
Average Power Output	1 kW
Efficiency	35%
Gain	20 dB
Cathode Voltage	7 kV
RF Input Impedance	50 ohms.

The phased-array objectives are as follows:

Frequency Range	3.0-3.6 GHz
Peak Power Output	2 kW
Duty	10 - 15%
Pulse duration capability with grid pulsing	100 μ sec
Grid cutoff voltage	1 kV max
Efficiency (incl. heater)	30% min
Gain	23 dB min
Line-to-sole voltage	10 kV max
In-Band power variation	+ 0.5 dB
Input/output connectors	Coaxial
Production cost objective	\$1,000 max

The performance objectives for I/J-band are as follows:

Frequency Range	8.5 - 17 GHz
Peak Power Output	1 kW
Average Power Output	200 W
Efficiency	30%
Gain	20 dB
Cathode Voltage	8 kV, max
Input Impedance	50 ohms

In previous programs for ERADCOM, operating E/F-band CFA's have been built which have demonstrated the effectiveness of the shaped substrate principle, first with a simulated shaped substrate [1] and then with a laser-cut shaped-substrate [2]. Performance was comparable with standard E/F-band CFA's. Tests of I/J-band cold-tests models were also made in contemplation of the I/J-band operating CFA's to be built as part of the present effort. It was necessary to develop appropriate new technology for cutting the shaped substrate from beryllia (BeO) ceramic, metallizing it, and bonding it to the co-expansive ground plane.

During the course of the present contract, an initial design for an I/J-band model was determined, based on large-signal calculations. It was clear from cold-test results that further I/J-band cold-test efforts are required. A new cold-test assembly has been designed which duplicates to a maximum possible extent, including common parts, the operating CFA design.

[1] Research and Development Technical Report No. ECOM-75-1343-1, Low-Cost Crossed-Field Amplifier, Final Technical Report, prepared by Northrop for U.S. Electronic Command, June 1977.

[2] Research and Development Technical Report No. ECOM-TR-77-2642-3, I/J-Band Crossed-Field Amplifier, Final Technical Report, April 1979.

The E/F-band design was reviewed to take into account the required greater gain in combination with lower peak power. It was concluded that a longer circuit is necessary.

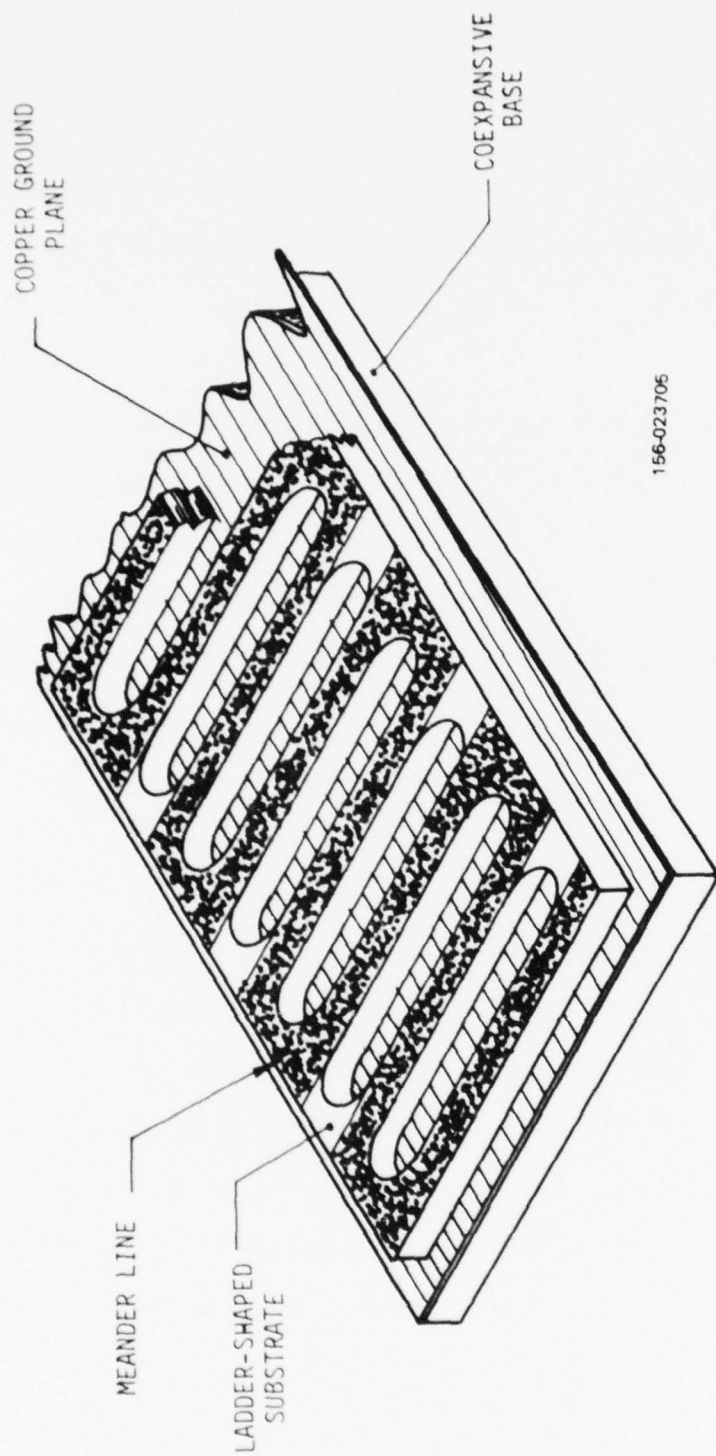
SECTION II

INITIAL STATUS

2.1 Technology

A major part of the effort on the previous contract [2] was the development of the necessary technology for fabricating the laser-cut shaped substrates, and for the assembly of the substrate with the co-expansive ground plane, and the meander circuit. The general concept is shown in Figure 1. It was found to be necessary to metallize the blank ceramic coupon before laser-cutting. Since the laser (CO_2) will not cut through copper, the metallized layer was etched in a meander pattern on one side, and laser cutting was performed where the metallizing was etched away. The resulting ladder-shaped substrates are quite fragile, especially for I/J-band dimensions. An additional problem encountered was the formation of tiny globules of BeO where the edge of a laser-cut slot meets the edge of the metallizing. These globules prevent the substrate from fitting closely to the ground plane and to the added-on meander. It was necessary to remove them by hand.

Some preliminary experiments showed that it may be possible to laser-cut the substrate after it is bonded to the ground plane, at least in I/J-band. This would alleviate the fragility problem. It would also eliminate the problem due to the ceramic globules at the interface between the substrate and ground plane. If the meander-shaped metallizing is thick enough that an add-on meander strip is not required, the globules are of no consequence if they are smaller than the thickness of the metallizing. Alternatively, the problem of globules might be corrected by modification of the laser-cutting procedure: feed rate, energy per pulse, pulse duration, etc.



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Figure 1: Meander Line on Ladder-Shaped Substrate and Coexpansive Base.

Bonding of the substrate to the co-expansive ground plane has been satisfactory provided that the composition of the ground plane material is 68% tungsten, 32% copper by volume.

2.2 E/F-Band CFA's

Two E/F-band CFA's with ladder-shaped substrates have been built and tested. The first showed peak power, efficiency, and bandwidth comparable with a CFA of conventional design, Northrop's RW-619. The second was apparently limited in peak power output by RF arcing, which could be circuit to ground or in the input or output connections. Such arcing was observed not only when the tube was operating, but also when RF power was fed in from an external source. To determine the cause of arcing it will be necessary to disassemble the tube for examination.

2.3 I/J-Band Cold-Test Models

The two I/J-band cold-test models were scaled from the ERADCOM E/F-band design, using a scale factor of 4/17 with respect to bar width so that the expected frequency corresponding to 90° phase shift per bar was about 14 GHz. The pitch was further modified so that the delay ratio would be about 12 at this frequency, a value considered appropriate for operation at a cathode voltage of 8 kV. Using these scale factors, pitch was 0.018" and to maintain the same pitch-to-thickness ratio the thickness should be about 0.006".

The first cold test model was made with an unmetallized substrate 0.010" thick. The substrate was cemented to a ground plane, and a photo-etched meander circuit was cemented to the top. Greater dispersion than desired was observed, as expected from the greater substrate thickness. Losses, on the basis of dB per delayed wavelength, were approximately as

expected on the basis of surface resistivity increasing as the square root of frequency.

The second cold-test model was made with a metallized substrate 0.006" thick, which was bonded to a co-expansive ground plane, and a photo-etched meander was then bonded to the substrate. Losses were much greater, and the delay ratio was much greater. The reasons for these differences from the first I/J-band cold-test model and from the E/F-band circuits were not clear. These anomalies must be resolved before building operating I/J-band CFA's.

SECTION III

E/F-BAND TUBES

The objective specifications for the E/F-band phased array application require more gain than for the electronic warfare application, and at lower peak power and therefore lower beam current. Less beam current leads to lower gain. On the other hand, the phased-array specification requires less bandwidth and the band center is above the center of the electronic warfare band. Since gain is greater at higher frequencies, the frequency range for phased array is more favorable in this respect.

Measurements corresponding to the phased-array requirement were made on the first ladder substrate CFA built during the previous program for ERADCOM [2]. Optimum efficiency for the 2 kW power level was found at a lower magnetic field setting than before, and a correspondingly lower value of cathode-to-ground voltage. Measurements were made from 3.0 to 3.6 GHz at 0.2 GHz intervals, and with RF drive power varied from 5 to 60 W. The results are shown in Figure 2. For full saturation, RF drive power of 40 W or more is needed. Therefore an increase of small-signal gain of 6 dB or more is desirable.

Small-signal calculations show that at least 6 additional circuit bars are needed. This is the greatest increase of length possible without major revision of the existing design. Therefore the existing E/F-band design was modified accordingly.

With the increased length, there is increased danger of instabilities in the electronic warfare mode, especially toward the high-frequency end of the band. It has been found possible to alleviate this problem by the

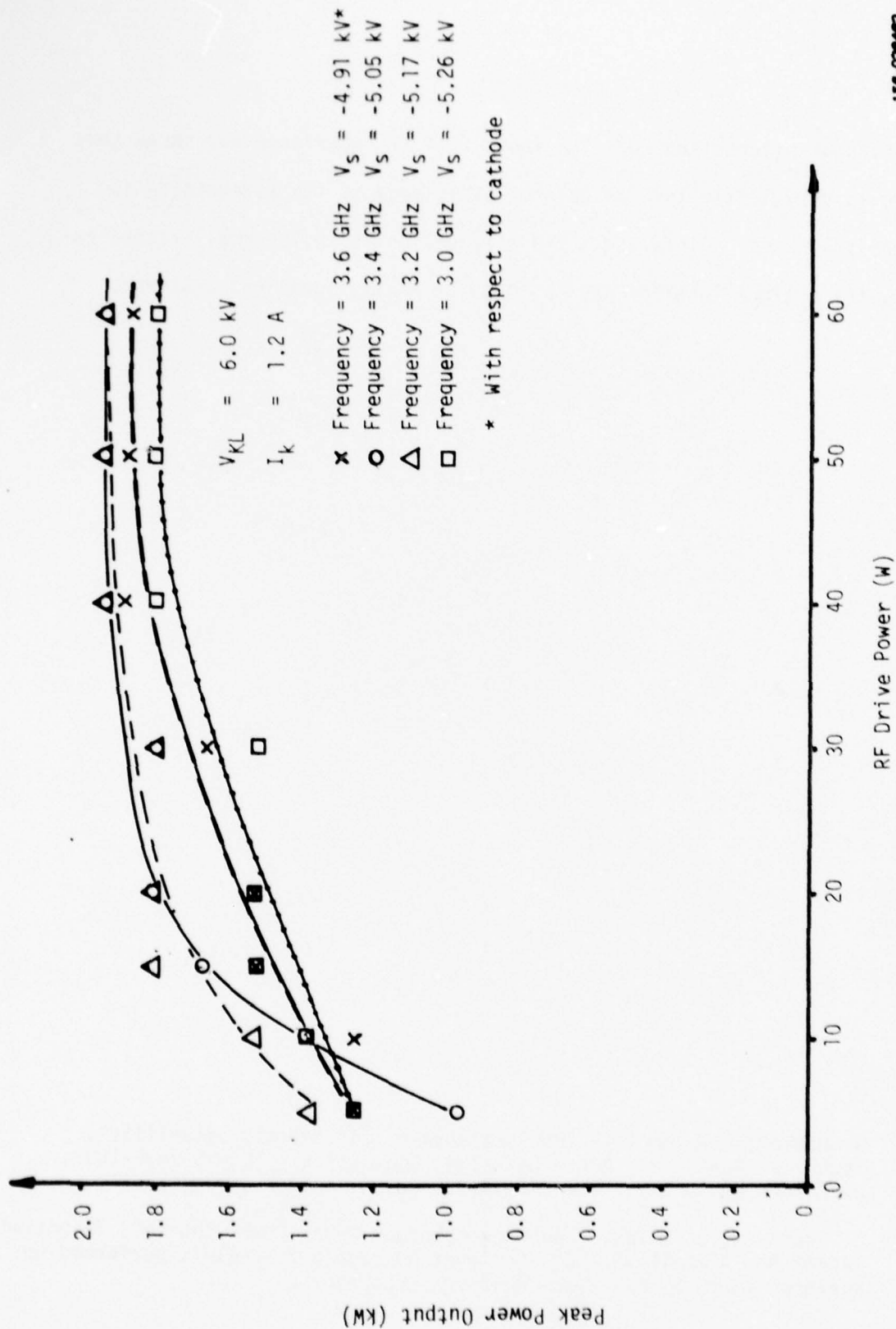


Figure 2: CFA Power Output as a Function of RF Drive

addition of attenuation near the input [3,4]. Experience has shown that there is very little loss of gain or efficiency if the attenuation is properly located. Since the added attenuation is in the small-signal region, the optimum location may be found by small signal calculations.

- [3] G. Dohler, R.R. Moats, "IBCFA Attenuator for Improved Stability", Technical Report No. AFAL-TR-77-134, Contract No. F33615-75-C-1098, performed by Northrop for U.S. Air Force Avionics Laboratory.
- [4] G. Groshart, D. Miley, "Low Cost Coherent Radar Power Source", Technical Report No. AFAL-TR-79-1060, Contract No. 33615-76-C-1147, performed by Northrop for U.S. Air Force Avionics Laboratory.

SECTION IV

I/J-BAND TUBES

4.1 Design Calculations

Small-signal and large-signal design calculations for an I/J-band operating CFA have been made. The circuit designs assumed were based on the cold-test data from the first I/J-band cold-test circuit made during the previous I/J-band development project for ERADCOM [2]. This circuit was not brazed, and the substrate was 0.010" thick as compared with the 0.006" thickness considered desirable from the standpoint of dispersion. Several values of pitch were selected for small-signal calculations, ranging from 0.012" to 0.018". Coupling impedance and dispersion (using phase velocity/group velocity as a measure) are assumed constant if the ratio of the gap between bars and the substrate thickness to the pitch is constant. Attenuation per bar is assumed to be due only to resistive losses and therefore is assumed to be inversely proportional to pitch.

There is a design trade-off between pitch and efficiency, with beam stability and power density to be dissipated on the circuit as considerations. Greater pitch has the advantage of lower attenuation per delayed wavelength, but requires a higher voltage beam. Beam current then will be less for a given power level, and gain per delayed wavelength will be less. To increase circuit efficiency, the ratio of rate of gain per unit length to attenuation per unit length must be increased. It has been shown [5] that on this basis, circuit efficiency increases indefinitely as pitch

[5] R.J. Espinosa, R.R. Moats "Broad-Band Injected-Beam Crossed-Field Amplifiers", IEEE Transactions on Electron Devices, Vol. ED-24, pp 13-21, Jan. 1977.

is decreased. The limitations are:

- (1) Beam instability, which can occur if beam impedance is too low.
- (2) Heat dissipation density of the circuit, which increases as gain per unit length increases.
- (3) Cathode loading, which must be greater for smaller pitch.

A series of small-signal calculations was performed based on the work of Gould [6] with values of pitch from 0.012" to 0.018". From these results, values of pitch of 0.014" and 0.016" were selected for large-signal calculations.

A series of large signal calculations was performed, using the computer code developed by Cooke, Dohler, and Shaw [7]. For the two values of pitch selected, line-sole spacing and B/B_{cr} (where B is applied magnetic field, B_{cr} is critical magnetic field*) were varied, subject to the constraint that $B > B_c$. The conditions for large-signal calculations are listed in Table I.

* $B_{cr} = V_{LS} \sqrt{2/\eta} V_{LC}/d$, where V_{LS} is sole-to-line voltage, V_{LC} is cathode to line voltage, η is the magnitude of charge-to-mass ratio of an electron, and d is sole-to-line spacing. If V_{ph} is given and equals electron velocity, then $B/B_{cr} = \sqrt{\eta V_{LC}/2} v_{ph}^2$

[6] R.W. Gould, "Space-charge effects in beam-type magnetrons," J. Appl. Phys., vol. 28, pp. 599-605, May 1957.

[7] M.L. Cooke, G. Dohler, and E.K. Shaw, "Crossed field amplifier (CFA) characterization and theory," Technical Report AFAL-TR-73-343, Air Force Avionics Laboratory, Wright-Patterson Air Force Base, Ohio, November, 1973. See also M.L. Cooke, E.K. Shaw, L.I. Yarrington, "The crossed-field amplifier, computational and experimental results," Technical Digest, International Electron Devices Meeting, IEEE, 1973.

TABLE I
Data For Large Signal Calculations

Run No.	1	2	3	4	5	6	7	8	9
RF Drive Power (W)		10			10			10	
Cathode-Line Voltage		8295			8295			6510	
Beam Current (A)		0.603			0.603			0.768	
Beam Width (ig)		0.118			0.118			0.118	
Line-Sole Distance (in)		0.0444			0.0493			0.0405	
Magnetic Field (Gauss)		4550			4095			4550	
Pitch (in)		0.016			0.016			0.014	
Frequency (GHz)	8.5	12.75	17	8.5	12.75	17	8.5	12.75	17
C/Ve	11.1	11.84	12.49	11.1	11.84	12.49	12.53	13.47	14.32
Coupling Impedance at Circuit (ohms)	50	45	35	50	45	35	56	51	43
Attenuation (dB/in)	2.82	4.22	5.64	2.82	4.22	5.64	3.68	5.51	7.34
Sole-to-Line Voltage (calculated for Synchronism)	13807	12981	12343	13789	12968	12335	11098	10372	9807
B/B _{cr} (calculated)	1.004	1.068	1.123	1.004	1.068	1.123	1.009	1.080	1.142

TABLE I
Data For Large Signal Calculations

Run No.	10	11	12	13	14	15	16	17	18
RF Drive Power (W)		10			10			10	
Cathode-Line Voltage		6510			8137			8137	
Beam Current		0.768			0.614			0.614	
Beam Width (ig)		0.118			0.118			0.118	
Line-Sole Distance (in)		0.0450			0.0400			0.0445	
Magnetic Field (Gauss)		4095			5690			5121	
Pitch (in)		0.014			0.014			0.014	
Frequency (GHz)	8.5	12.75	17	8.5	12.75	17	8.5	12.75	17
c/v _e	12.53	13.47	14.32	12.53	13.47	14.32	12.53	13.47	14.32
Coupling Impedance at Circuit (ohms)	56	51	43	56	51	43	56	51	43
Attenuation (dB/in)	3.68	5.51	7.34	3.68	5.51	7.34	3.68	5.51	7.34
Sole-to Line Voltage (calculated for synchronism)	11083	10362	9802	13796	12879	12161	13805	12892	12177
B/B _{cr} (calculated)	1.001	1.081	1.143	1.121	1.201	1.272	1.122	1.201	1.272

Coupling impedance and delay ratios (c/v_{ph}) were estimated for substrate thickness of 0.006". The coupling impedance and dispersion are slightly higher for 0.014" pitch because the substrate thickness is greater in proportion to pitch.

The input data are listed and results plotted in groups of three runs. Each group represents one set of operating parameters at each of three frequencies, with the sole voltage adjusted for synchronism at each frequency. The first two groups, runs 1-3 and 4-6, use assumptions corresponding to pitch of 0.016" and B/B_{cr} of just over 1.0 for the lowest frequency. Runs 1-3 have smaller sole-line spacing and correspondingly greater magnetic field than runs 4-6. The remaining runs correspond to pitch of 0.014". Runs 7-9 and 10-12 all represent conditions for which B/B_{cr} is just over 1.0 for the lowest frequency; runs 7-9 have smaller sole-line spacing and greater magnetic field than 10-12. Runs 13-15 and 16-18 represent conditions for which B/B_r is significantly greater than 1.0 and runs 13-15 represent smaller line-sole spacing and greater magnetic field than 16-18.

Results of the calculations, showing power on the circuit as a function of distance from RF input, are shown in Figures 3 through 8. Each figure shows results for one group of three runs. In each figure then it is necessary to select a circuit length which is an optimum compromise. At low frequencies, gain is low; at high frequencies, electrons are intercepted quickly by the circuit and the power is then attenuated by the circuit.

In examining the calculated results, in all cases it is clear that smaller sole-to-line spacing is desirable. When βd is greater than 5.5 for 17 GHz, the rate of gain is too low, and is especially low in runs 6 and 18.

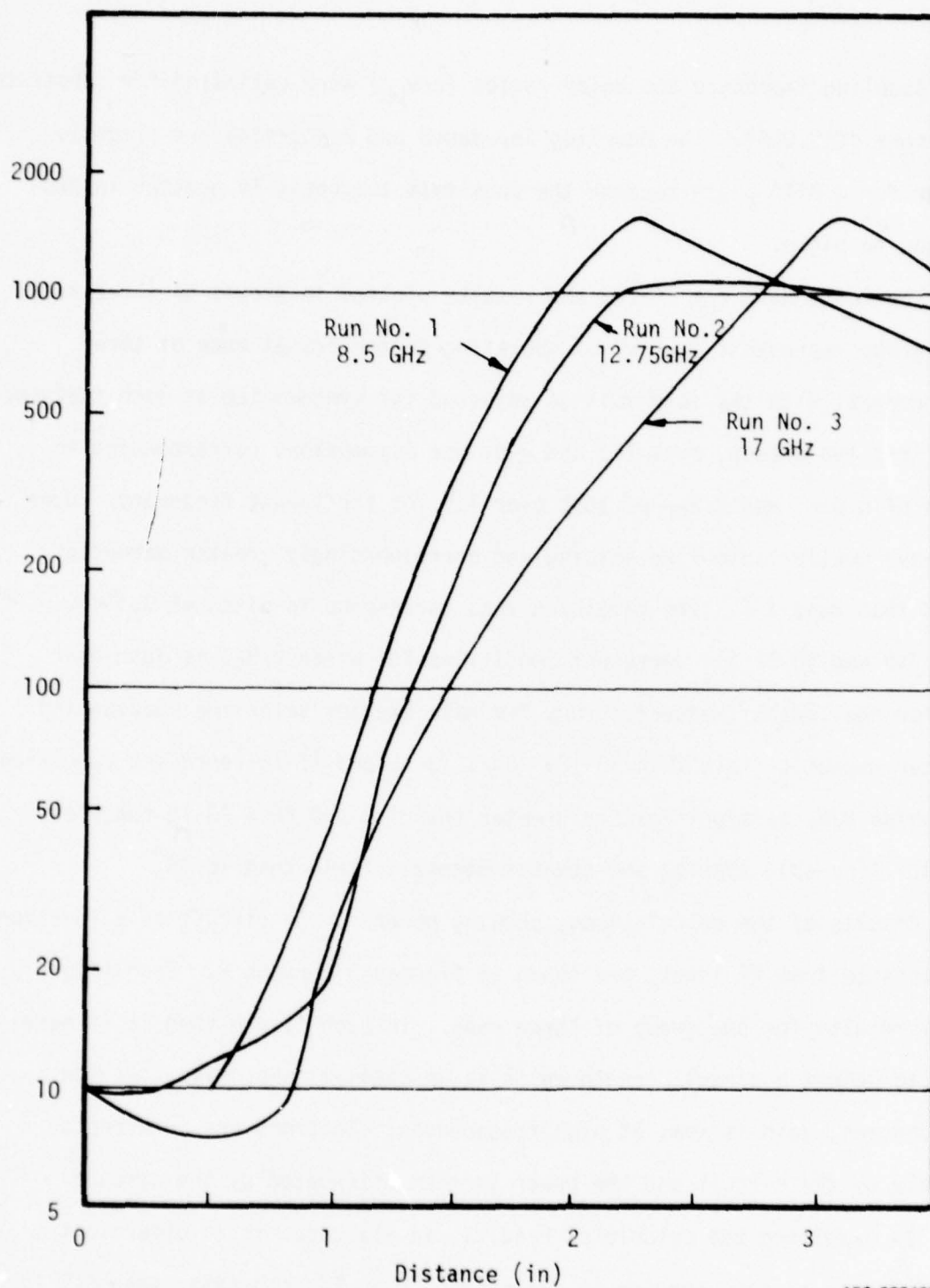
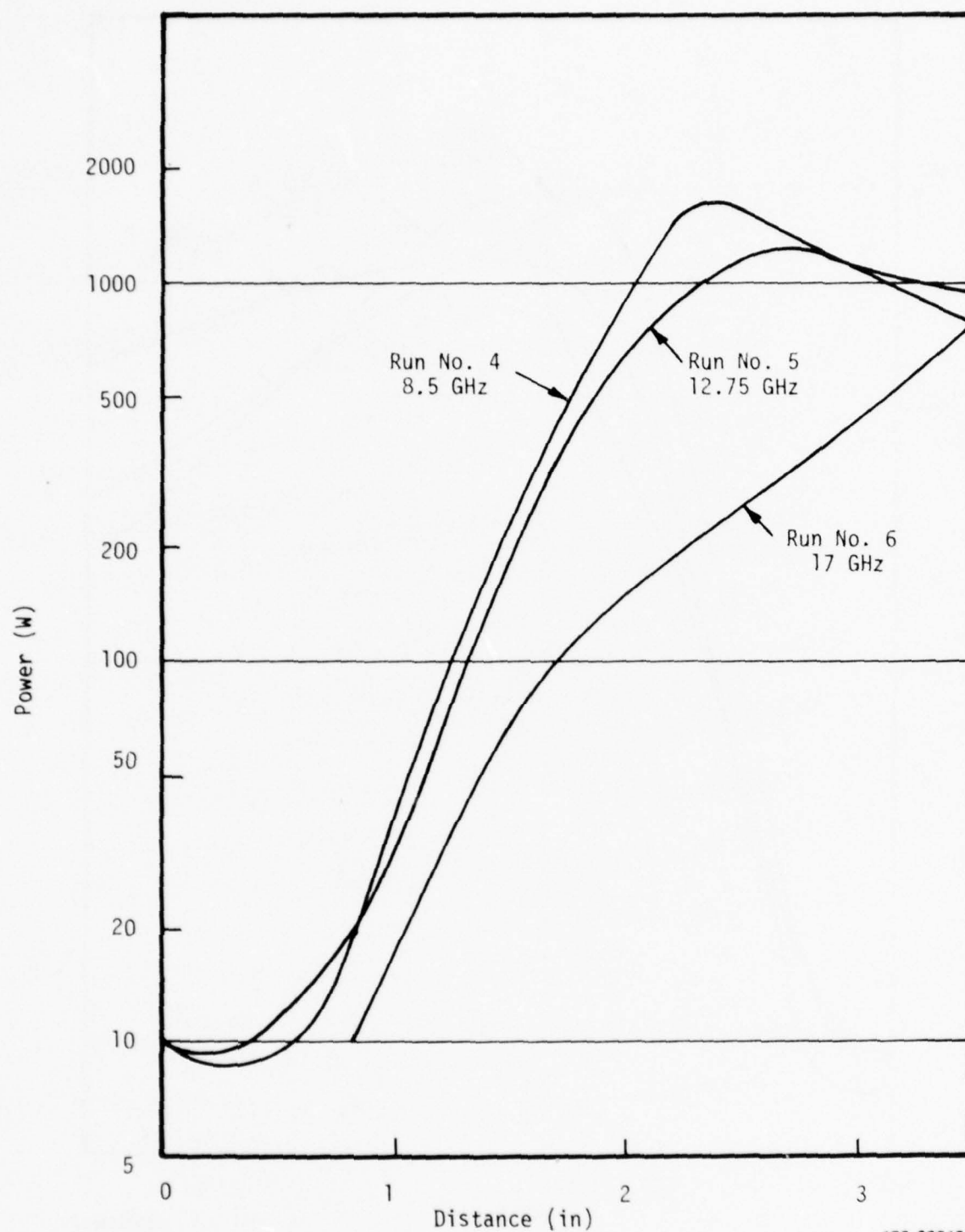


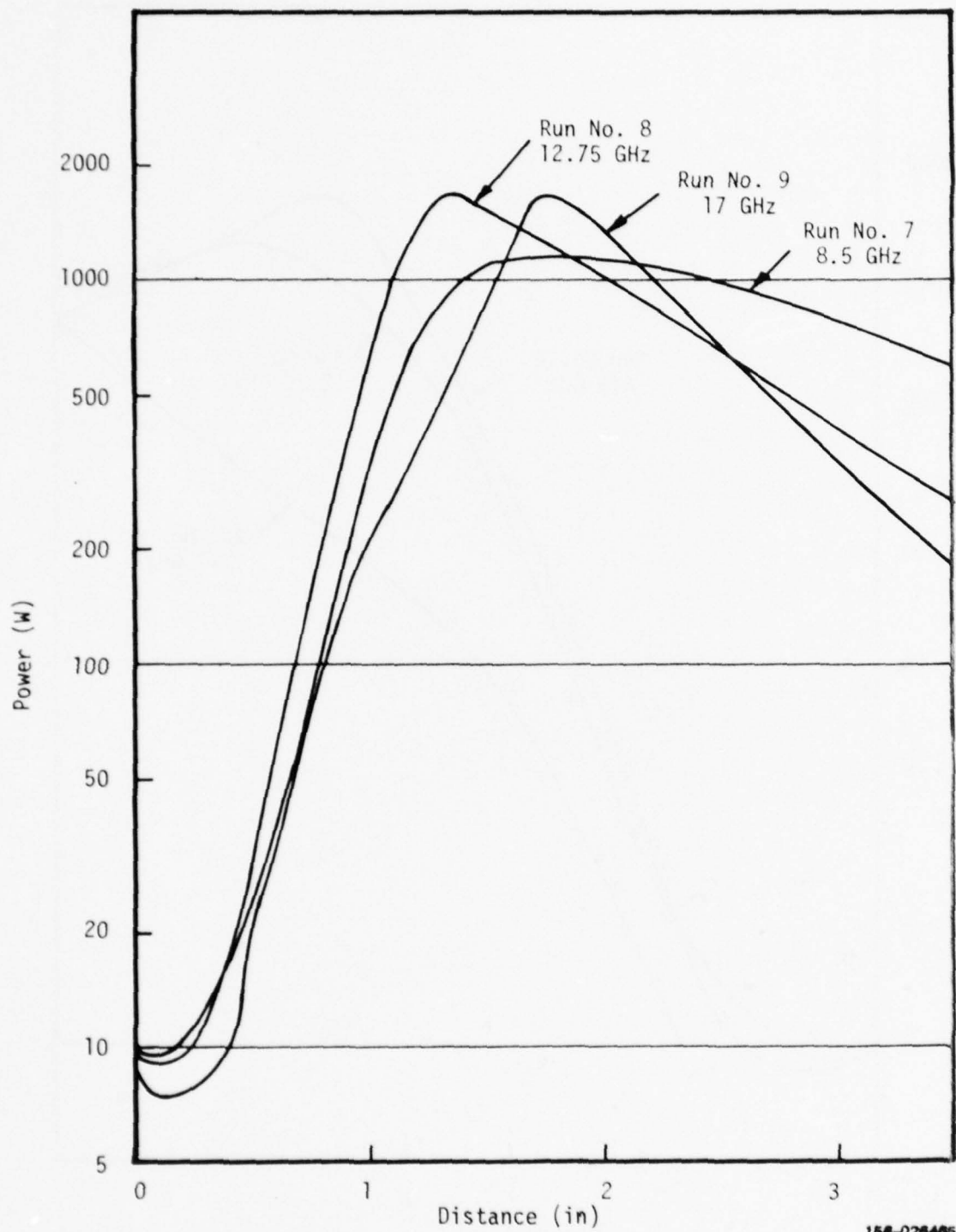
Figure 3: RF Power from Large-Signal Calculations
(Runs 1-3)

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Figure 4: RF Power From Large-Signal Calculations
(Runs 4-6)



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Figure 5: RF Power from Large-Signal Calculations
(Runs 7-9)

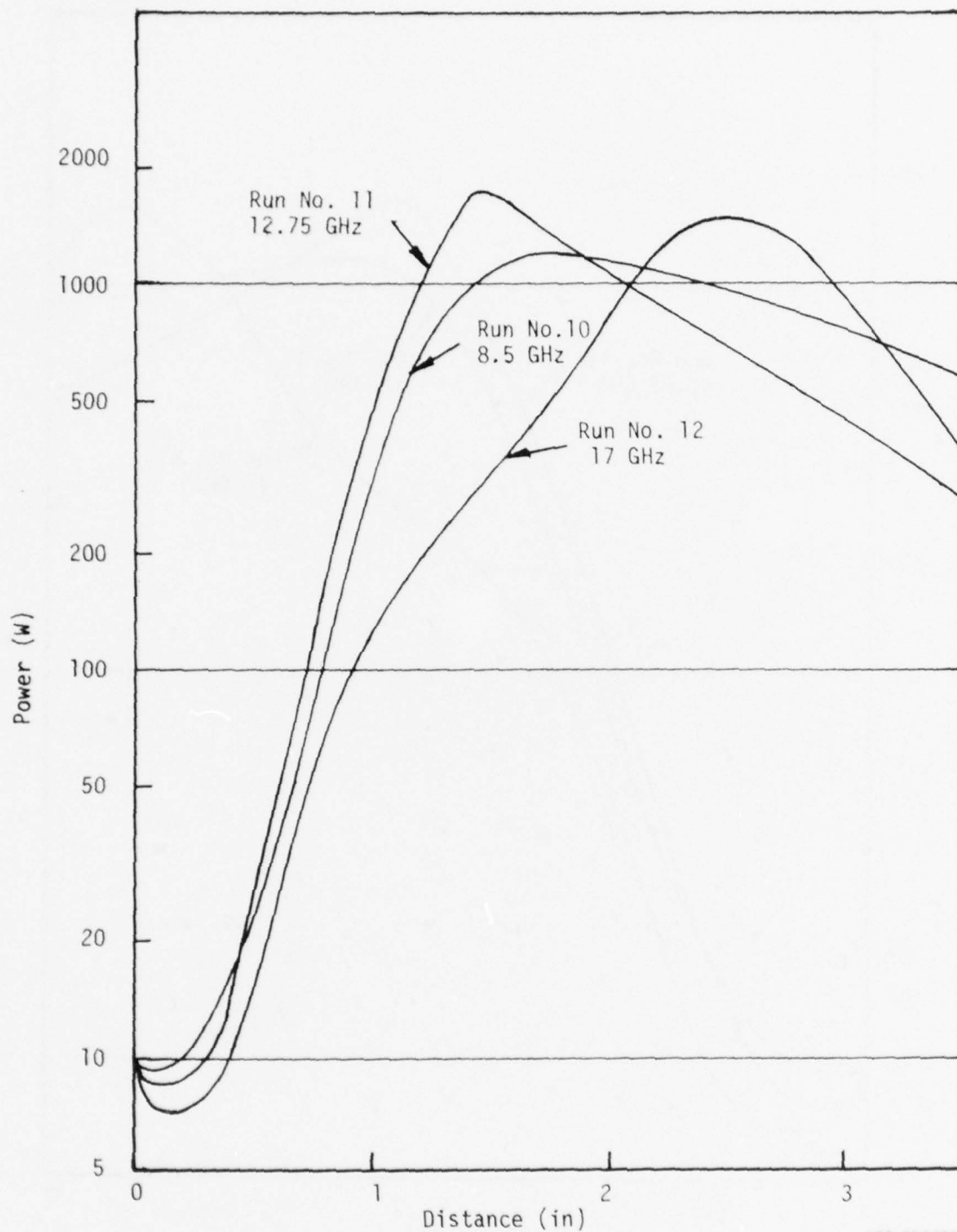


Figure 6: RF Power from Large-Signal Calculations
(Runs 10-12)

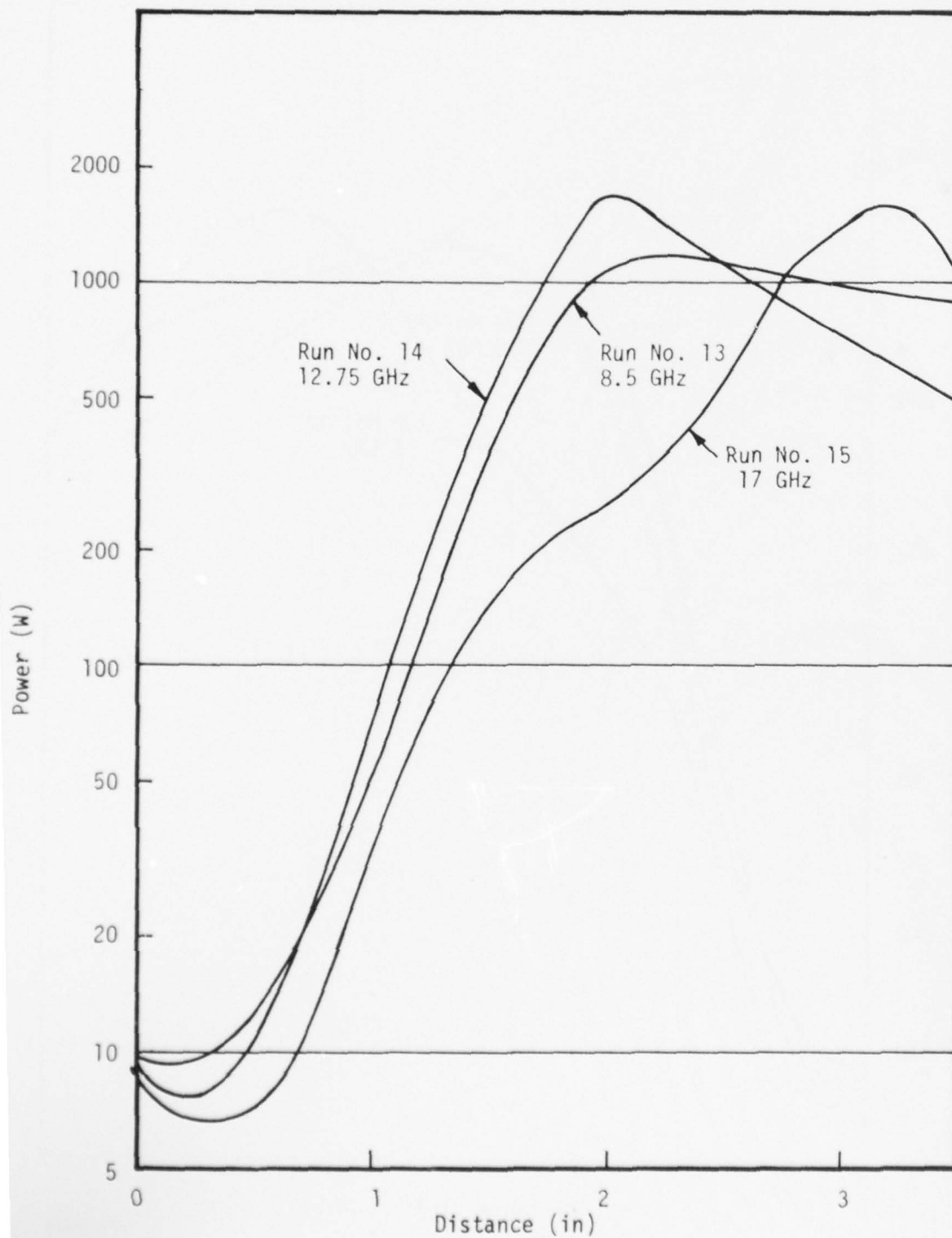
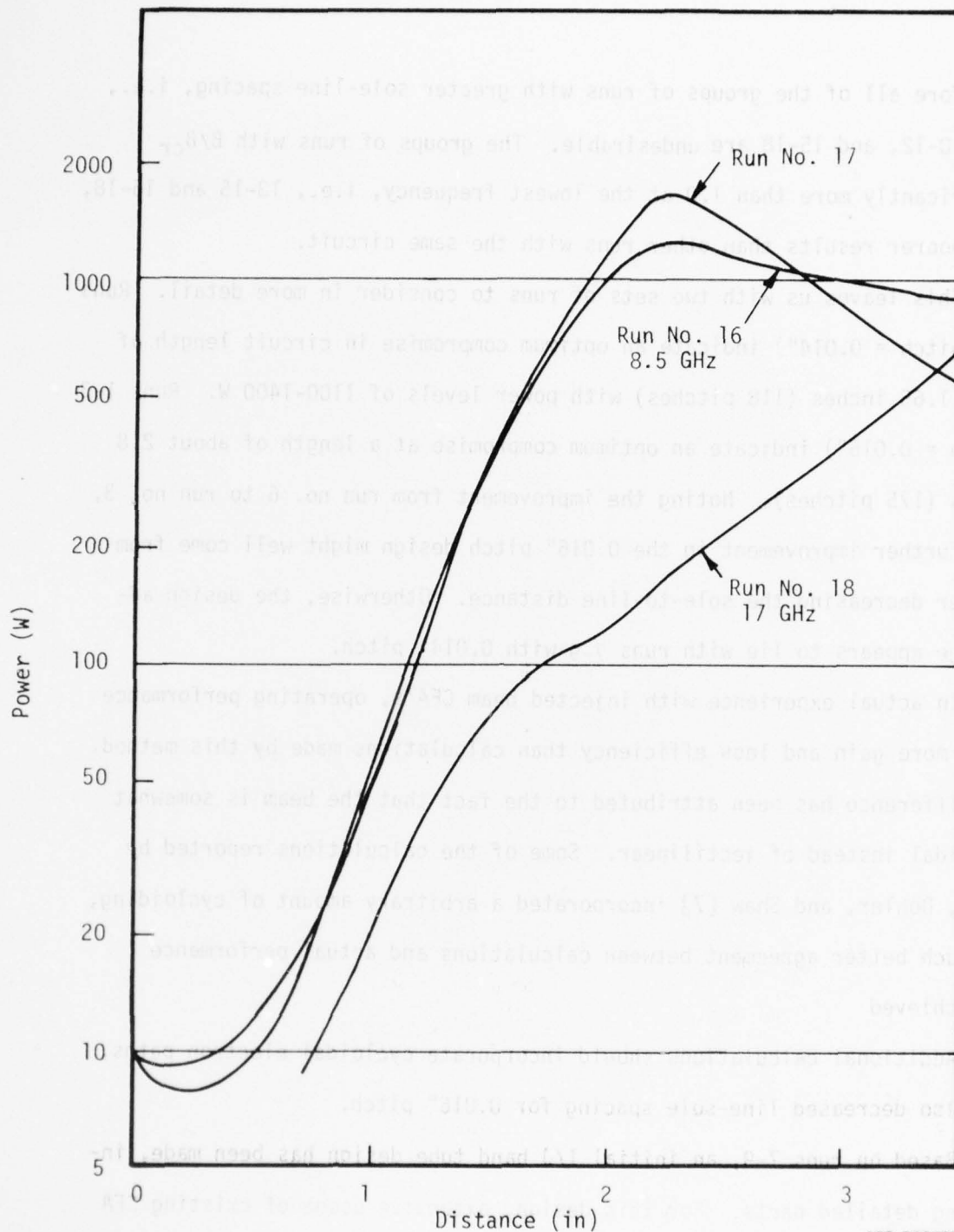


Figure 7: RF Power from Large-Signal Calculations
(Runs 13-15)

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Figure 8: RF Power from Large-Signal Calculations
(Runs 16-18)

Therefore all of the groups of runs with greater sole-line spacing, i.e., 4-6, 10-12, and 15-18 are undesirable. The groups of runs with B/B_{Cr} significantly more than 1.0 at the lowest frequency, i.e., 13-15 and 16-18, show poorer results than other runs with the same circuit.

This leaves us with two sets of runs to consider in more detail. Runs 7-9 (pitch = 0.014") indicate an optimum compromise in circuit length of about 1.65 inches (118 pitches) with power levels of 1100-1400 W. Runs 1-3 (pitch = 0.016") indicate an optimum compromise at a length of about 2.8 inches (175 pitches). Noting the improvement from run no. 6 to run no. 3, some further improvement in the 0.016" pitch design might well come from further decreasing the sole-to-line distance. Otherwise, the design advantage appears to lie with runs 7-9 with 0.014" pitch.

In actual experience with injected beam CFA's, operating performance shows more gain and less efficiency than calculations made by this method. The difference has been attributed to the fact that the beam is somewhat cycloidal instead of rectilinear. Some of the calculations reported by Cooke, Dohler, and Shaw [7] incorporated an arbitrary amount of cycloiding, and much better agreement between calculations and actual performance was achieved.

Additional calculations should incorporate cycloidal electron paths, and also decreased line-sole spacing for 0.016" pitch.

Based on runs 7-9, an initial I/J band tube design has been made, including detailed parts. For this design, extensive usage of existing CFA parts was incorporated into the design.

4.2 I/J Band Circuit

In previous work directed toward these objectives[2], some anomalies were observed in the second I/J-band cold-test circuit which was built and tested. The delay ratio was much greater than had been predicted, and the attenuation was also much greater than expected on the basis of scaling laws and from results of the first I/J-band cold-test model. Some of the values of attenuation which were measured would be unacceptably high in any operating CFA. This cold-test model differed from the first one in that the substrate was metallized and the assembly was brazed. An additional difference was that the substrate was 0.006" thick, as compared with 0.010" thick for the unbrazed model.

Possible reasons for those differences not easily accounted for by the difference in substrate thickness include:

- (1) Assembly imperfections: An additional etching step after brazing was required because of an assembly error.
- (2) Excess losses at the ceramic-metal interface.
- (3) Errors in measurement, for example due to excess radiation observed because of poor transition from the input coaxial line to the meander circuit.

A possible cause of increased losses at the interface is the thickness of the molybdenum barrier layer. Considering a copper circuit with a molybdenum surface layer, it is found that when the molybdenum is a substantial fraction of a skin depth thick, the surface resistivity approaches that of molybdenum rather than copper. Relative surface resistivity of such a surface as a function of frequency with molybdenum thickness as a parameter is shown in Figure 9. The sputter metallizing processes at Northrop have been reviewed

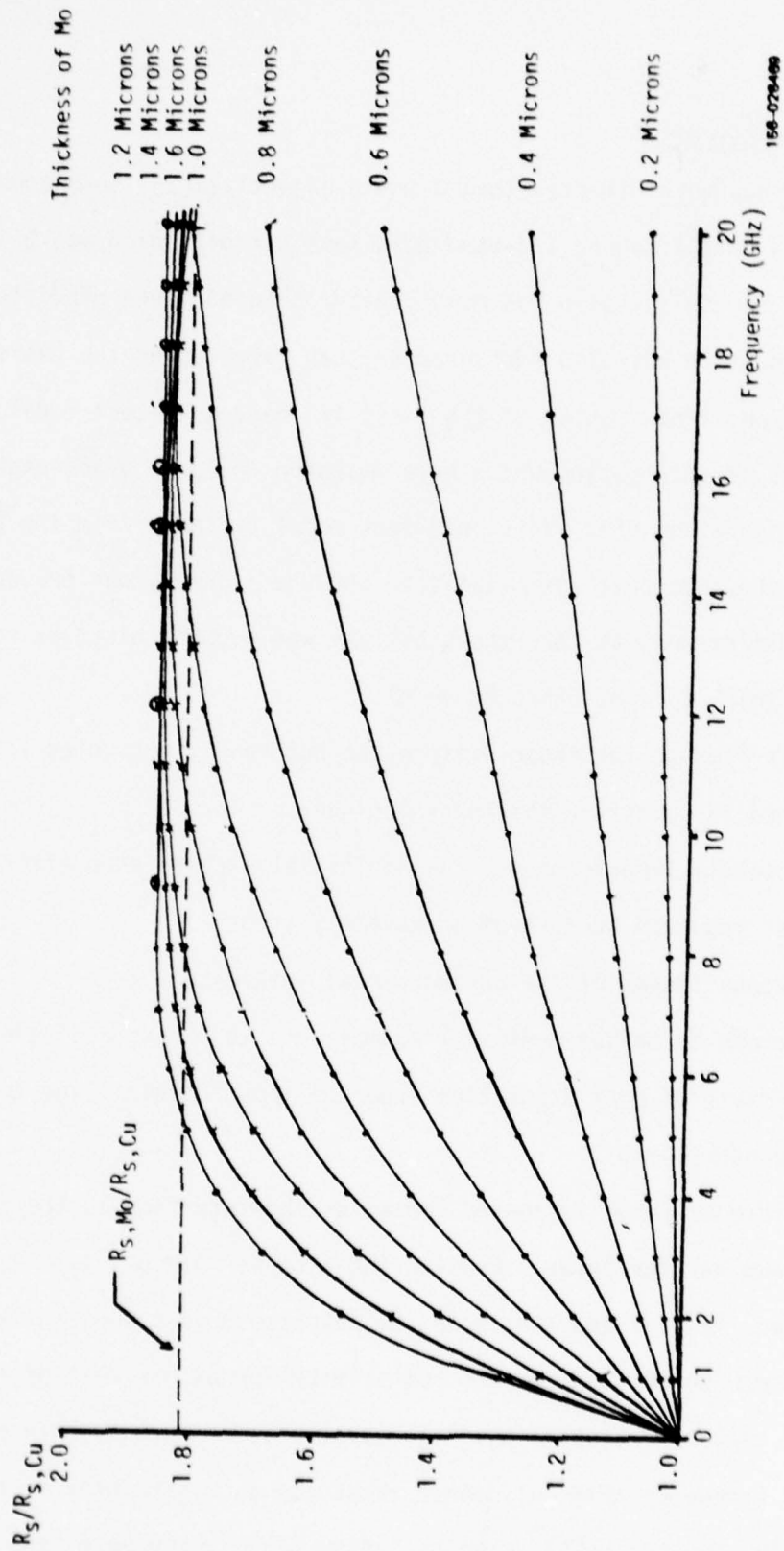


Figure 9: Surface Resistance of Cu Plated with Mo as a Function Of Coating Thickness and Frequency

recently. It was found that the rate of deposition of molybdenum was about 1.7 times as great as had been supposed. This difference could have contributed to higher attenuation, but could not account for increases by as much as 2 to 1 at some data points.

It was originally believed that useful data could be obtained without careful attention to RF matching. Delay ratio can be measured from standing waves observed with amplitude detection. Attenuation can be measured from the Q's of resonances. Coupling impedance can be measured from the perturbation of resonance frequencies. However, excessive radiation is still a suspected cause of anomalous test results.

The first step toward resolving these apparent problems is to repeat the second cold-test experiment by making another similar structure with parts which are immediately available. This will eliminate any possible adverse effect due to the extra etching procedure, such as undercutting the copper meander.

For further tests, a cold-test fixture has been designed in which the circuit configuration is identical to the initial design for operating I/J-band CFA's, including the input/output connections, the dimensions of the circuit based on large-signal runs 7-9, and the method of construction. The construction of such assemblies for cold testing will make possible the determination of the input/output design including suppression of radiation. The thickness of the meander will be varied from the minimum consisting of the metallized layer only, up to at least 0.003" and a further variation will include a 0.003" thick meander with 0.001" overhang on each side of the ceramic substrate cross-bars.

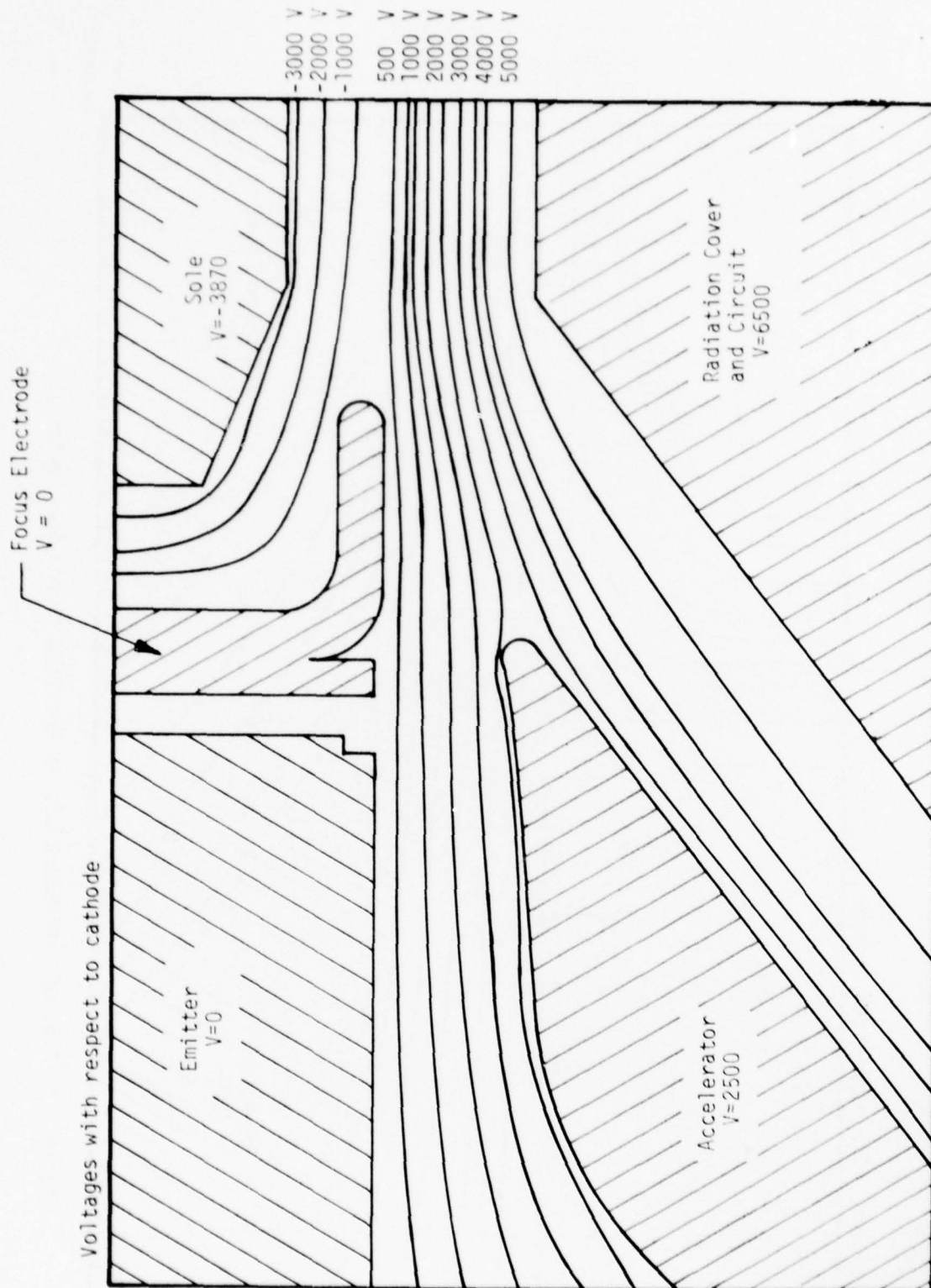
4.3 I/J-Band Gun

The first set of I/J-band gun design concepts was described in [2]. The design was modified to correspond to the beam parameters of large-signal runs 7-9 (see Table I). After initial parts drawings were made, equipotential lines were plotted by means of resistive paper, giving the results shown in Figure 10 for the long Kino gun version. A requirement for good beam quality is that the electric field should increase monotonically along the electrode trajectory. If this condition is met, and if there are no abrupt changes in the field, some latitude in the shape of the electric field is tolerable. In Figure 10 there is found some distortion of the equipotential lines in the vicinity of the "nose" of the focus electrode, where the equipotentials spread apart corresponding to a reduction of electric field. A modification of this gun design is shown in Figure 11. The principal difference is the thinner nose of the focus electrode. A very significant improvement in the shape of the equipotentials is observed. The latter design was adopted and parts are now being made. Design work for a gridded version is in progress.

Testing of these guns for beam quality in Northrop's crossed-field beam tester [8,9] is contemplated. It has been determined that the magnet structure now present in the beam tester is capable of providing the necessary 4500 Gauss over the required gap length.

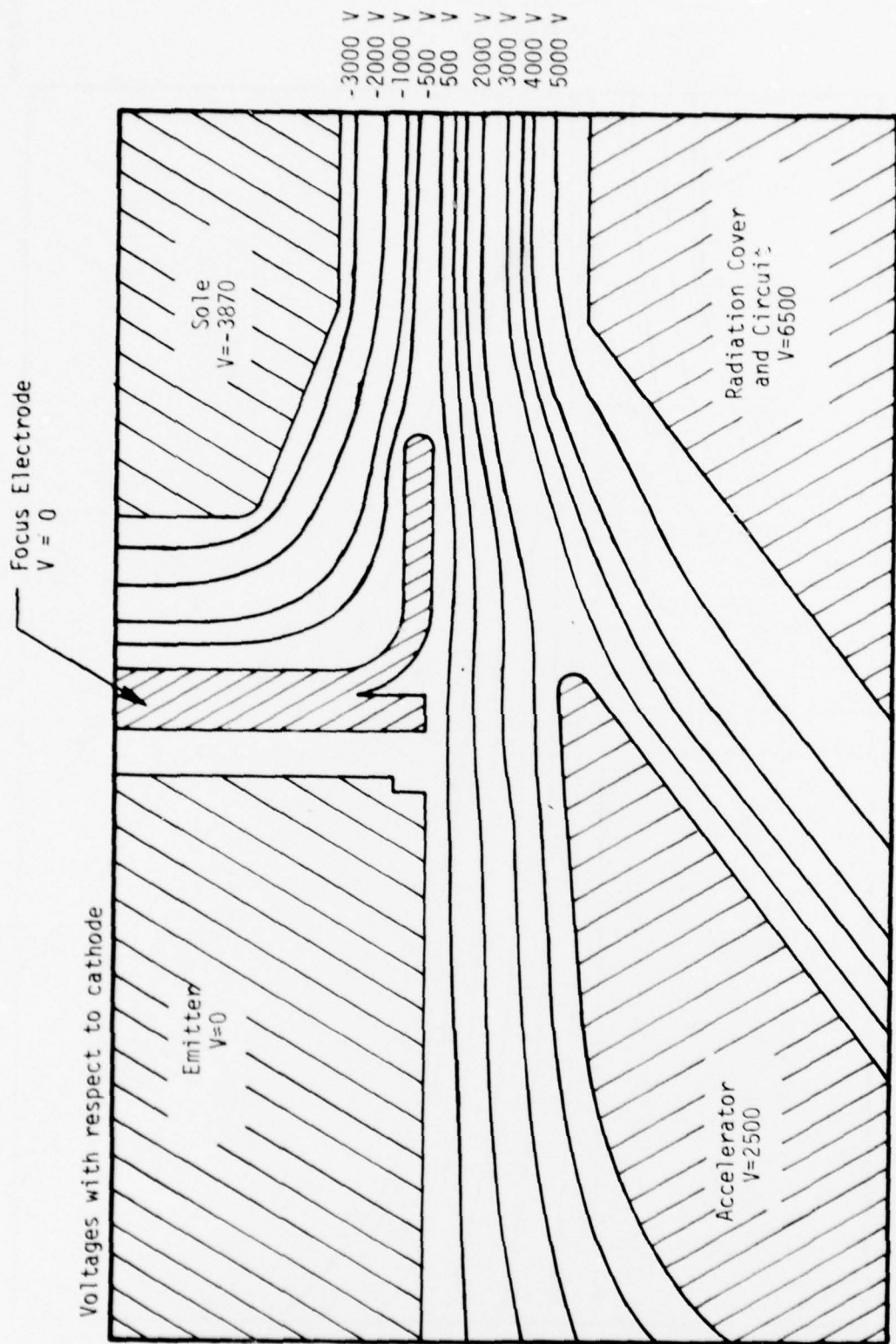
[8] O. Doehler, G. Dohler. "IBCFA Gun Design by Quantitative Beam Analysis," Report No. AFAL-TR-78-7, Contract No. F33615-75-C-1033, Air Force Avionics Laboratory.

[9] Contract No. F33615-78-C-1435, Air Force Avionics Laboratory.



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Figure 10. Plot of Equipotentials in Initial "Kino" Gun Design



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Figure 11: Plot of Equipotentials in Modified "Kino" Gun Design

4.4 Input/Output Coaxial Window

Reflection measurements on coaxial windows of two existing designs have been made. One, which is intended for an I/J-band TWT and is still in process of development, showed a peak value of VSWR greater than 4:1 at 9 GHz and generally high VSWR above 13 GHz. The other, which was designed for an X-band CFA, showed VSWR of less than 1.25:1 up to about 14 GHz, above which the VSWR increased abruptly. Results are shown in Figure 12. The sharp increase in VSWR above 14 GHz is attributed to the $TM_{0,1}$ mode, for which the cut-off frequency is calculated to be 14.5 GHz.

The latter design should be amenable to scaling so that the sharp increase in VSWR falls above 17 GHz. Since this window was designed to be capable of 20 kW peak power output and has so far been tested above 7 kW, the slightly smaller window (from scaling) should give no trouble at 1 kW peak.

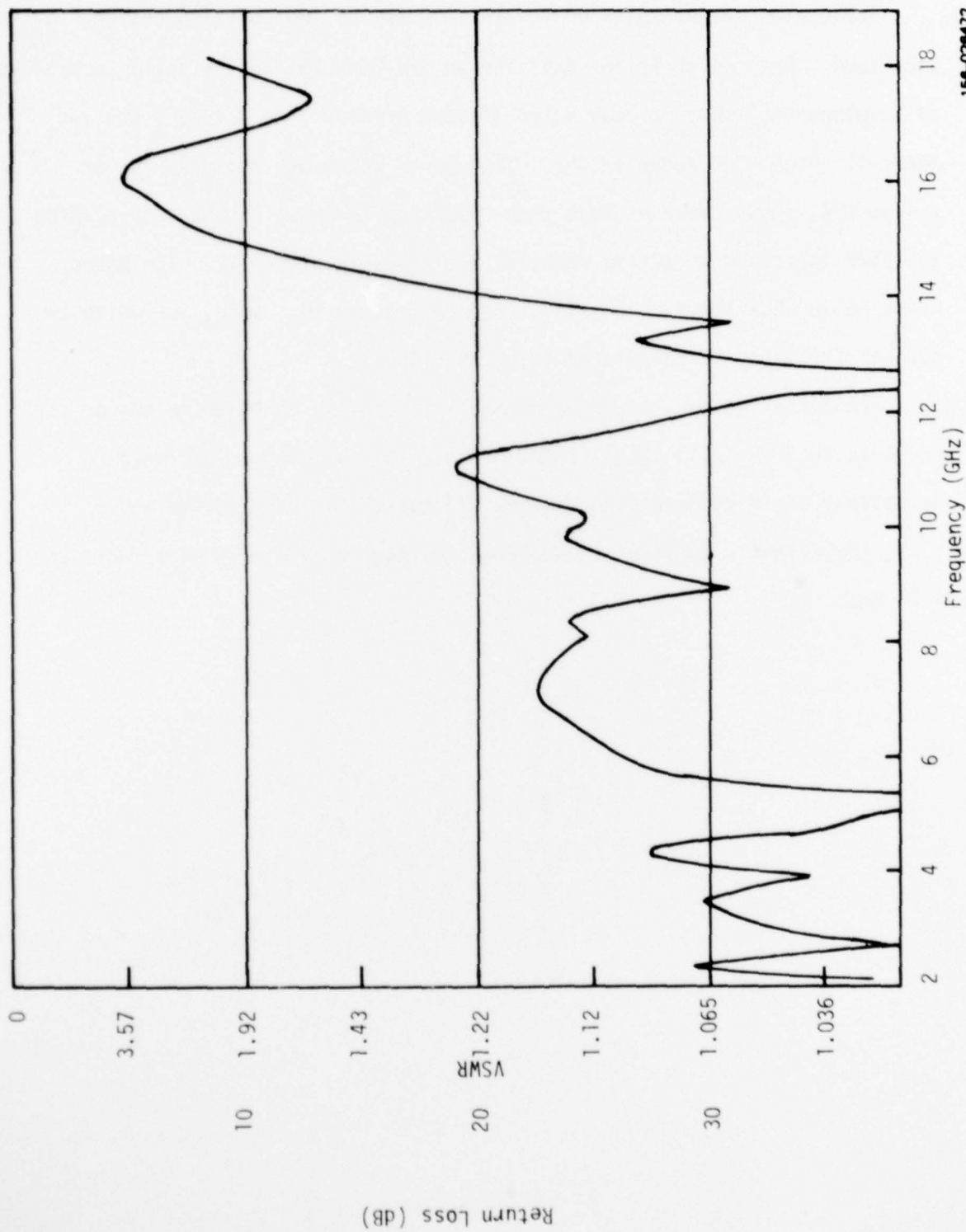


Figure 12: Matching of Coaxial Window Designed for X-Band CFA

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SECTION V

TECHNOLOGY

Two experiments were performed to determine the effectiveness of bonding ceramic and copper to the copper-tungsten composite material which is used for the co-expansive ground plane. Since the bonding of the ceramic is accomplished by copper-to-copper diffusion at high temperature and high pressure, it is necessary that a copper layer be deposited on the surface of the composite, and that this layer be thick enough to yield under pressure sufficiently to make a good bond, and to suppress the effect of the surface irregularities of the composite material. It is suspected that previous bonds which have been made were not sufficiently strong. For the tests reported here, the copper layer was deposited by sputtering to a depth of about 11 μm (0.0004"). In the past the depth has been of the order of 0.0001" or less.

For the ceramic bonding experiment, a ceramic coupon 0.017" thick (the thickness used for E/F-band) was sputter metallized according to the pattern which has been generally used at Northrop for E/F-band and G/H-band CFA's:

Titanium:	800 Å
Molybdenum:	8500 Å
Copper:	60000 Å

The coupon was cut into 0.5" squares, and two of them were bonded to pieces of copper-tungsten composite which were copper coated as described above. At the same time, copper pull-test rods 3/8" in diameter with waffle-iron faces were brazed to each face of the sandwich of the ceramic and composite. Pull tests of the two assemblies were performed with the following results:

(1) 210 lbs., 8235 psi

(2) 212 lbs., 8313 psi

The effective area, 0.0255", is the area of the waffle iron face of the pull test rods. Failure in each case occurred on the side where the pull-test rod was bonded to the ceramic, thus indicating the strength of the ceramic-to-copper bond. The ceramic-to-composite bond, where there was no indication of failure, was subjected to an average stress of only about 840 psi. The localized stress may have been substantially greater because the ceramic thickness (0.017") was small compared with the size of the waffle-iron segments (0.0425" square).

A similar pull test was applied to a piece of the composite material only. Using similar pull-test rods, failure occurred at 332 lbs, or 13,000 psi. A piece of composite was copper plated instead of copper sputtered, and a peel test showed that the adhesion of the plating was much poorer than the sputtered copper. It must be concluded that if copper plating is to be considered as a cost reduction measure, a major improvement in the process is needed.

To gain additional information as to the soundness of the ceramic-to-composite bonding, a thermal test fixture is under construction. This

fixture will make it possible to test the assembly of meander line, substrate, and ground plane separate from the rest of the tube assembly. The fixture is a water-cooled plate with means for clamping the assembly to be tested. A current of about 30 A (DC or 60 Hz) is passed through the meander to heat it, and the temperature difference between the meander and the cold plate, or between the meander and the ground plane, is measured by thermocouple. From the applied power and the dimensions of the substrate, it is possible to calculate the effective heat conductivity.

SECTION VI

FURTHER WORK TO BE PERFORMED

6.1 E/F-Band CFA's

The design of an E/F-band CFA suitable for both the electronic warfare application and the phased array application has been substantially completed. The effort in the next reporting period will be directed toward making parts and beginning assembly. In addition, the pattern for adding a section of attenuation on the circuit near enough to the input to avoid serious degradation of efficiency will be established. Such added attenuation has been demonstrated to improve stability quite significantly, and is considered desirable for the new design because the greater length will increase the tendency toward spurious oscillations. The attenuation is applied by sputtering a thin layer of resistive material onto the assembly of meander line, substrate, and ground plane.

6.2 I/J-Band CFA

The most important task to be accomplished for I/J-band during the next reporting period is the design of the meander circuit. The data assumed for circuit characteristics in the large signal calculation was based primarily on cold test results derived from the unbrazed I/J-band cold test model for which the substrate thickness was 0.010". The data for the first brazed I/J-band cold-test model, in which the substrate thickness was 0.006", were somewhat suspect. Another similar model will be constructed using available parts. In addition, cold-test models with 0.014" pitch, and using various configurations of meander, will be built and tested. Further large-signal

An actual-size model of the first design of electron gun is to be built and tested in the crossed-field beam tester. This will require some modification of the beam tester, as well as the construction of the gun.

The first cold-test model of the coaxial window design will be unbrazed and built with a bead made of synthetic dielectric instead of ceramic to allow quick modifications. From this we will proceed to coaxial windows made of materials suitable for operating tubes.

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